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Anomalous Resistivity on Auroral Field Lines

H. L. Rowland and K. Papadopoulos

Laboratory for Plasma and Fusion Energy Studies
University of Maryland, College Park, MD 20742

and

P. J. Palmadesso

Geophysical and Plasma Dynamics Branch
Plasma Physics Division

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ANOMALOUS RESISTIVITY ON AURORAL FIELD LINES

INTRODUCTION

The understanding of acceleration processes in the auroral zones, due to parallel electric fields ($\underline{E}_{\parallel}$), is closely connected with the problem of one-dimensional anomalous resistivity and the breakdown of runaway acceleration. The one-dimensional aspect of the problem comes from the fact that in the auroral regions of interest (i.e., $h > 1000$ km), $\Omega_e/\omega_e \gg 1$ (where ω_e, Ω_e are the plasma and cyclotron frequencies). In this case, the Larmor radius of the electrons is less than the Debye length, so that even in the case of ion acoustic turbulence of Debye length scales, the magnetic moment of the electrons ($\mu = mv_\perp^2/2B$) is an adiabatic invariant. The weak magnetic field case ($\omega_e \gg \Omega_e$) results related to anomalous resistivity are not directly applicable. This is obvious since the physical process by which anomalous resistivity results when $\omega_e \gg \Omega_e$, is the interaction of electrons with low-frequency fluctuations which has the form of elastic scattering. The rapid scattering of the electrons then converts the directed velocity into heating and the appearance of anomalous resistivity. For $\Omega_e \gg \omega_e$, the elastic scattering is not allowed since μ is constant and the electrons can only slow down by parallel diffusion. However, as noted by Petviashvilli [1], the parallel diffusion is accompanied by the formation of a quasilinear plateau, which reduces the anomalous friction and produces trivial resistivity changes, independently of the amplitude of the low-frequency waves. A corollary puzzle is what, if anything, inhibits the electrons in the plateau region as well as the negative slope region from freely accelerating [2,3]. If distributed parallel electric fields are to exist in the auroral regions, the above questions should be answered.

The purpose of the present report is to demonstrate that under conditions prevailing in the aurora, the conservation of the first adiabatic invariance is violated for electrons above a certain threshold velocity. This effect combined with trapping a major portion of the electron distribution function, by large amplitude ion cyclotron waves such as observed by S3-3 [4] and in laboratory experiments [5], is sufficient to answer the major questions posed above and reproduce most of the observed features of the auroral energetic electron fluxes.

PHYSICAL MODEL

Consider a plasma in a uniform magnetic field $\underline{B}_o$ with $\Omega_e \gg \omega_e$, and an electric field $\underline{E}_o$, parallel to $\underline{B}_o$, which causes the electrons to acquire a drift velocity v_d large enough to drive an ion cyclotron wave. There are two basic questions to be answered. First, what ultimately limits the growth? Second, what, if anything, inhibits the electrons from freely accelerating?

Several processes have been discussed in the literature for limiting the growth [6,7]. In view of the recent experimental evidence for large-amplitude ($\delta n/n \approx 1/2$) coherent ion cyclotron waves in the aurora [4] we consider here trapping as the basic stabilization mechanism. The effect of large-amplitude, low-frequency density fluctuations on the plasma resistivity has been recently examined by Rowland et al. [8]. It was shown, by including the quasineutrality effect, that most of the electrons can be trapped for $\delta n/n > 1/4$. The electron distribution function is composed of a central part carrying little or no current, and a runaway tail of density n_r due to the untrapped electrons,

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which carry the current. Therefore $J(t) = n_r e v_r(t)$ where the ratio n_r/n is controlled by the level of $\delta n_i/n$; as shown in Rowland et al. [8], while in the absence of a mechanism that can break the adiabatic invariance of the energetic electrons, $v_r \approx (eE_o/m)t$. From the above we see that the existence of a steady or quasisteady state reduces to the answer to the second question, i.e., the mechanism that can inhibit the free acceleration of runaways.

To answer this question, we examine the stability of distributions which are composed of a cold core with a runaway tail. The linear stability was studied by Kadomtsev and Pogutse [9], who showed that low-frequency oscillations $\omega_k = \omega_e k_\parallel/k \ll \Omega_e$, where $k_\parallel$ is the wave vector along the magnetic field, are unstable even for flat distributions. These modes are principally driven by the first cyclotron resonance at velocities $(\omega_k + \Omega_e)/k_\parallel$. The instability has a growth rate $\gamma_k \approx n_r/n\ (\omega_e/\Omega_e)^2 \omega_k$. The nonlinear theory of the instability has been studied extensively [3,10,11]. It was shown there that it results in a fast isotropization for particles with velocities $v_\parallel > v_c \approx 3(\Omega_e/\omega_e)v_{te}$ (v_{te} is the electron thermal velocity). A consequence of this is the breakdown of the adiabatic invariance for electrons with $v_\parallel > v_c$. An additional slowing down process was discussed first in Papadopoulos et al. [12] and confirmed by particle simulations by Haber et al. [11]. Since only particles with $v_\parallel > v_c$ participate in the resonant scattering and have their $v_\parallel$ reduced, electrons will tend to pile up at v_c leading to the formation of a beam. This distribution function can suffer friction in the parallel direction due to wave emission not only by the cyclotron resonance but also by Cerenkov type beam plasma instability at the lower or upper hybrid branch. Moreover in the presence of a constant dc electric field this piling up can be enhanced by particles being accelerated up from lower velocities. This reappearance of an electron beam and the slowing down of the electrons in the parallel direction will further isotropize the electron distribution function.

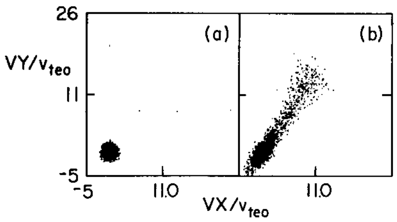
Another interesting effect that is seen in the simulations is the acceleration of particles in the opposite direction to the electric field. The electrostatic waves that are generated in the parallel direction can be backscattered by the ion fluctuations and create superthermal tails by Landau damping. These particles can also interact via the normal Doppler resonance $[v = (\omega_k - \Omega_e)/k_\parallel]$ with the waves that are pitch angle scattering the runaways and isotropize the counter streaming particles.

SIMULATIONS

We report next the results from a series of particle simulations that combine the effects of finite ion cavities and pitch angle scattering at the anomalous Doppler resonance (ADR). The parameters for the simulations are the same as those used by Haber et al. [11]. However, instead of starting with a runaway distribution, we start with a Maxwellian distribution and a fixed ion cavity with an effective depth of 0.3. We will apply a constant dc field to show the formation of the runaway distribution such as was seen in the earlier strictly one-dimensional simulations of Rowland et al. [8]. We will then continue to drive the electrons to determine the effect of the pitch angle scattering on the further acceleration of the electrons.

Figure 1(a) shows the initial electron distribution. The magnetic field is at 55° to the x axis and $\Omega_e = 2\omega_e$. The electric field is parallel to B and has a magnitude of $0.01(m/e)v_{teo}\omega_e$ [where $m(e)$ is the electron mass (charge), v_{teo} is initial electron thermal velocity, and ω_e is the plasma frequency]. Figure 1(b) shows the electron velocity distribution at 2000 ω_e^{-1}. The ion cavity has prevented the bulk of electrons from being accelerated, and one can see the cold dense core of electrons at zero velocity. The untrapped electrons accelerated along the magnetic field forming a flat runaway tail. One can see that the temperature of the electrons transverse to the field did not increase, and up to this point the acceleration was $1D$ parallel to the magnetic field. However, the

Fig. 1 — The initial $1D$ acceleration of the electrons parallel to the magnetic field B and E_o is at 55° to the axis. (a) initial distribution, (b) distribution at 2000 ω_e^{-1}. The ion cavities prevent the acceleration of the bulk of the electrons.



high-velocity edge of the distribution has become greater than v_c, and these particles started to pitch angle scatter as seen by the spreading of the upper edge of the distribution.

At this point in time, that $2D$ effects started taking place, the simulation was stopped. This state was used as an initial state for a series of simulations using different values for the external dc electric field. Our earlier theoretical and computational work (Rowland et al. [8]) demonstrated that during the initial $1D$ stage, changing the strength of the dc electric field did not affect the formation of the runaway distribution beyond changes in the timescale; namely with a stronger electric field the runaway distribution formed faster. The simulation presented in detail here had an electric field starting from 2000 ω_e^{-1} of magnitude $2 \cdot 10^{-3}(m_e/q)\, v_{teo}\omega_e$. As the pitch angle scattering continues, the formation of a beam in the parallel direction similar to the one seen by Haber et al. [11] is observed. The region of positive slope is unstable to Cherenkov interactions with both lower and upper hybrid waves. This acts to reduce the parallel current and to further symmetrize the distribution. Figure 2(a) shows the distribution at 3800 ω_e^{-1}. No further parallel acceleration of the electrons is observed. Electrons with $v_\parallel > v_c$, which could be pitch angle scattered to large $v_\perp$, were slowed down by the beam instability. Thus one sees electrons with $v_\parallel < v_c$ but with $v_\perp \gg v_{teo}$. This isotropization continues. Figure 2(b) shows the electron distribution function at 8800 ω_e^{-1}. It is composed of a cold dense core of electrons surrounded by a hot, isotropic cloud.

Figure 3 shows the parallel electron distribution at 2400, 3200, 4800, 8800 ω_e^{-1} (a,b,c,d). The high-velocity beam seen at 2400 ω_e^{-1} is due to the pitch angle scattering. By 3200 ω_e^{-1} beam instabilities have flattened the runaway distribution. It is clearly seen that the instability at the anomalous Doppler resonance prevents electron runaway. If the high-velocity electrons had continued to freely accelerate, the upper edge of the distribution would have been at the right-hand edge of Fig. 3(d).

Figure 4 shows the growth of the parallel drift velocity normalized to the *initial* electron thermal velocity. Note that the time axis between 0 and 2000 ω_e^{-1} is stretched by a factor of five to compensate for E_o being five times larger during that time. Thus the time axis is linear in terms of the effective acceleration time, $E_o t$. Between 0 and 150 ω_e^{-1} the ion cavity was adiabatically formed in the plasma. At 150 ω_e^{-1} the dc electric field was turned on. The solid line shows for comparison the rate of acceleration of the electrons in the absence of the cavity. Between 150 and 2000 ω_e^{-1} we have essentially a $1D$ system parallel to the magnetic field. The cavities prevent the acceleration of the bulk of the plasma, and the current is carried by a small fraction of high-velocity electrons streaming along the field lines. At approximately 2000 ω_e^{-1} the velocity of the fastest particles exceeds v_c and pitch angle scattering begins; the high-velocity electrons are heated in the transverse direction with $v_\perp$ becoming greater than v_{teo} and the adiabatic invariance is broken. The current continues to increase until approximately 2300 ω_e^{-1} when the instability at the ADR has grown to such a level that it removes energy from the parallel motion and slows the electrons down faster than E_o accelerates them. The current is clamped, and strong transverse heating is observed. Finally, at much longer times ($\gtrsim 7000\ \omega_e^{-1}$) the current begins to increase again but at a slower rate than during the $1D$ stage. For $v_\parallel > v_c$ the instability heated the plasma so that $\partial f/\partial v_\parallel \approx \partial f/\partial v_\perp$

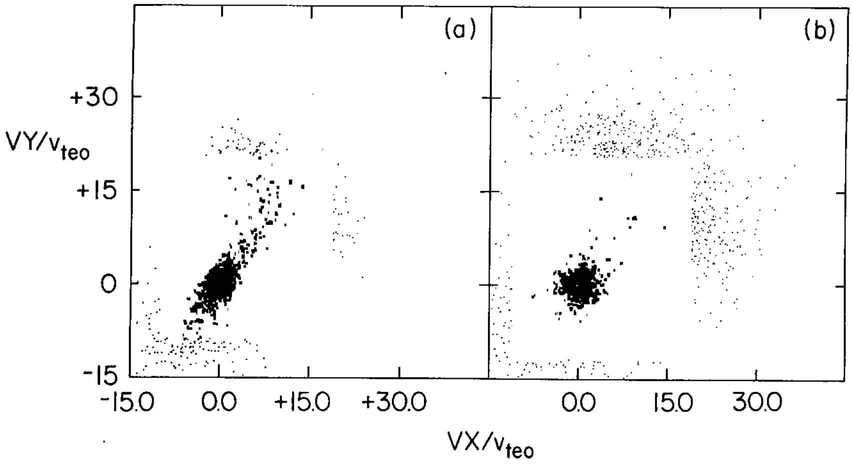


Fig. 2 — As the electrons continue to accelerate $v > v_c$, the pitch angle scattering breaks the invariance of 0 and strong transverse heating sets in. (a) $t = 3800\ \omega_e^{-1}$, (b) $t = 8800\ \omega_e^{-1}$.

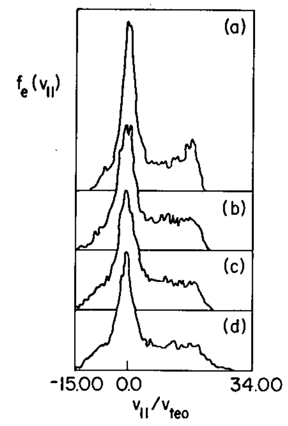


Fig. 3 — The parallel electrons distribution. The pitch angle scattering prevents the free streaming acceleration of the electrons t = 2400, 3200, 4800, 8800 ω_e^{-1} (a,b,c,d).

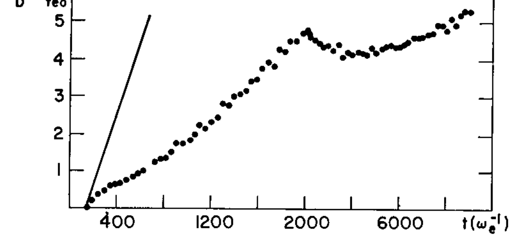


Fig. 4 — The average electron drift velocity. When $v > v_c$, the pitch angle scattering clamps the current.

(or $T_{\parallel} \approx T_{\perp}$). The electric field can begin to increase $v_{\parallel}$ for these particles but the rate of increase is slowed due to pitch angle scattering which acts to keep $T_{\parallel} \approx T_{\perp}$. The increase in the current can be seen in Fig. 3. The cutoff at v_c is still being maintained but a few particles are accelerated to higher velocities.

Figure 5 shows the log of the electron distribution at $t = 8800\ \omega_e^{-1}$. A cold dense core of trapped electrons surrounded by the hot isotropic accelerated electrons is seen. This distribution has marked similarity to the auroral electron distributions measured by Kaufmann et al. [13].

CONCLUSIONS

The acceleration in the auroral zones is, of course, a spatial problem. While temporal simulations such as reported here are very important for understanding the basic microphysics that takes place in the auroral environment, large scale macrophysics simulations are needed. The present results are a necessary input before a complete understanding of the total system dynamics can be gained. Development of such a capability is presently under way. We present a qualitative picture of the macrostructure expected on the basis of our simulations. The first point is that for the pitch angle scattering to be effective requires $\Omega_e/\omega_e \gtrsim 1$. Thus one would expect to see strong dc resistivity and parallel electric fields between 2000 to 12 000 km. The critical value of the current at which strong resistivity appears, increases with Ω_e/ω_e. Thus there exists a maximum critical current that can be carried along the field line. Below this level the ion cavities prevent the bulk of the electrons from being accelerated and tails of field aligned electrons are formed. However, when this critical current is exceeded one expects the emission of both upper and lower hybrid waves, large parallel electric fields, and a hot isotropized electron distribution with a cold dense core. The strongest resistivity and hence the largest electric fields will appear in the region where the current is clamped. One can make a rough estimate of the initial extent of this region by assuming $\Delta r = v\tau$ where v is the speed of the high-velocity particles and τ is the time over which the current is clamped. For the simulation shown $\tau \approx 4.10^3\ \omega_e^{-1}$. Assuming $n_p \approx 100$ cm and a velocity of a keV electron this leads to a distance of 200 km. This is of course only a rough order of magnitude estimate but the main point is that the resistivity and the parallel electric fields should extend at least initially over a large region in comparison to the Debye length ($\approx$3 m). This is in agreement with a recent analysis of satellite data of potential drops along auroral field lines [14]. The dynamic spatial behavior is a subject for further study but this region could shrink. For the simulation shown in detail the dc electric field $E_o = 2.7 \cdot 10^{-4}\ T_e^{1/2} n_p^{1/2}$ (where T_e is in eV, n_p is plasma density in cm^3, and E_o is in V/m) for $t > 2000\ \omega_e^{-1}$. For $T_e = 20$ eV and $n_p = 100$, $E_o \simeq 10^{-2}$ V/m and $\Delta\phi \simeq E_o \cdot \Delta r = 2$ keV. Based upon our series of simulation $\tau \propto E_o^{-1}$. For constant $\Delta\phi$, reduction of Δr would lead to a larger E_o. This, in turn, would lead to a shorter τ and further reduction of Δr. On the other hand, if the system responds by raising ϕ in order to drive a $j > j_{cr}$, an increased E_o and a shorter Δr will result. Such questions can only be studied with a large scale transport code.

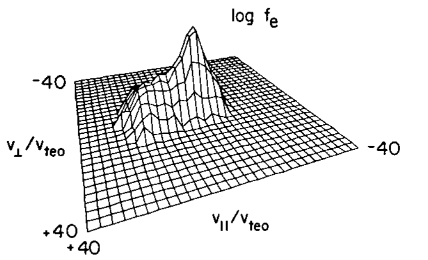


Fig. 5 — A 3D plot of the log of the electron distribution seen in Fig. 2(b). Note the cold central core and the hot isotropized electrons.

Another spatial effect presently under study is the anomalous transport of the hot electrons across the magnetic field and out of the acceleration region. If this takes place at a fast enough rate such that $T_\perp$ remains less than $T_\parallel$, the current will remain clamped. In this case τ will be determined by the timescale for this perpendicular transport.

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